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Parametric and Cycle Tests of a 40-A-hr Bipolar Nickel-Hydrogen Battery

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SUMMARY

A series of tests was performed to characterize battery performance relating to certain operating parameters which included charge current, discharge current, temperature and pressure. The parameters were varied to confirm battery design concepts and to determine optimal operating conditions.

Spacecraft power requirements are constantly increasing. Special spacecraft such as the Space Station and platforms will require energy storage systems of 130 and 25 kWh, respectively. The complexity of these high power systems will demand high reliability, and reduced mass and volume. Candidate electrochemical systems are regenerative fuel cells, nickel-cadmium batteries and nickel-hydrogen batteries.

A system that uses batteries for storage will require a cell count in excess of 400 units. These cell units must then be assembled into several batteries with over 100 cells in a series connected string. In an attempt to simplify the construction of conventional cells and batteries, the NASA Lewis Research Center battery systems group initiated work on a nickel-hydrogen battery in a bipolar configuration in early 1981.

Features of the battery with this bipolar construction show promise in improving both volumetric and gravimetric energy densities as well as thermal management. Bipolar construction allows cooling in closer proximity to the cell components, thus heat removal can be accomplished at a higher rejection temperature than conventional cell designs. Also, higher discharge current densities are achievable because of low cell impedance. Lower cell impedance is achieved via current flow perpendicular to the electrode face, thus reducing voltage drops in the electrode grid and electrode terminal tabs.

BATTERY AND CELL DESIGN

The battery tested was a 12 V (10 cell), 40 A-hr, bipolar battery. The battery was actively cooled with five inter-cell planer cooling plates. The cooling system was operated in the temperature range of 0 to 40 °C; allowing full thermal characterization and determination of appropriate operating temperature.

Accommodations were made for oxygen and electrolyte management. These two functions take place within an electrolyte reservoir plate that contains the oxygen recombination sites. Water, the product of recombination, equilibrates with the electrolyte of the nickel electrode. These functions and other design details are explained in greater depth in a previous paper (ref. 1).

TEST PROCEDURES

Two initialization cycles were performed prior to characterization. The cycle regime was a C/10 (5.0 A), 13-hr charge and a C/4 (12 A) discharge terminated when the first cell reached 0.5 V. A value of 50 A-hr was used for the capacity, C, which had been determined from previous tests results. The ampere-hours obtained on discharge for the first cycle were 49, and 50 on the second cycle. The results proved that this new battery design could provide the predicted results.

Battery performance was characterized by carrying out a series of parametric tests. Data were obtained at the following conditions: charge rates of C and C/2; discharge rates of 2C, C and C/4; temperatures of 0, 10, 20, 30 and 40 °C; base pressures of 200 and 400 psi.

Temperatures were maintained by circulating a nonconductive inert fluid through the five cooling plates of the battery. Temperatures were adjusted at static conditions and allowed to stabilize until the inlet and outlet coolant temperatures were equal. The coolant bath temperature was maintained to within 0.1 °C by the chiller/heater unit.

The hydrogen pressure was also adjusted at the static discharged condition. The amount of hydrogen generated on charge was small compared to the free volume of the test chamber. Thus, the pressure increase from discharged to full charge was only about 25 psi.

TEST RESULTS

Data taken for each charge/discharge cycle were as follows: individual cell voltages, temperatures, ampere-hours and watt-hours. Values were updated and integrated every 18 sec with a digitizing voltmeter. Both charge and discharge current levels were held constant with power supplies and electronic discharge devices.

Tables I and II display the test results of ampere-hours, watt-hours and end-of-discharge battery voltage. The remaining battery capacity was drained at the 12 A rate (C/4) when the discharge rate was greater than C/4. Charge input was 56 A-hr for each test matrix point. The data presented in table II, 400 psi gas pressure, was a modified matrix where effects of hydrogen gas pressure could be observed at those conditions of greatest interest. Table III shows characterization data obtained at all pressure and temperature levels at the same charge rate of 2 hr and the same 50 A (the C rate) discharge. The decision was made to increase the charge input to 65 A-hr for this series of tests for two reasons:

- (1) The C/4 drain resulted in total discharge capacities of 54 A-hr several times, thereby creating a situation of possible charge deficiency.
- (2) To minimize the influence of varying levels of charge acceptance of the nickel electrode at different temperatures.

Special tests were also conducted to determine battery performance beyond the normally expected range of conventional space power systems. High discharge rates and pulse discharge capabilities were tested because the bipolar

battery has exhibited good performance in this area as previously reported (ref. 2).

The battery was high rate discharged at both constant and pulsed currents for the 250 A (5 C) and 500 A (10 C) rates to a discharge cutoff voltage of 6.0 V during the pulse. Both voltage performance and capacity at pulsed conditions increased as shown in figure 1. One additional pulse test was to discharge the battery at 1500 A (30 C) for 1 sec where a load voltage of 4.0 V was established resulting in a 6 kW pulse. This value was lower than expected from previous results (ref. 2). This lower value of pulse power and the result of a dramatic increase in high rate capacity by pulsing compared to constant discharge level indicated that possibly the area for hydrogen gas access in the frames was not sufficient to support these high discharge rates. This problem was addressed by redesigning the gas access slots in future batteries for pulse applications.

Figure 1 also shows plots of the data tabulated in table I. Figure 1 displays battery voltage and discharge capacity as a function of discharge current at 20 °C. The 12, 50, and 100 A discharge plots are characteristic of classical battery performance plots. However, the constant load discharge curves of 250 and 500 A do not have the standard plateau and knee. This is because of the high rate discharge and possibly the decrease of hydrogen gas concentration at the electrode surface. These two tests were repeated by pulse discharging at a 1 sec on, 1 sec off duty cycle. The off, or relaxation time allows the gas concentration to increase in the gas cavity formed by the hydrogen electrode, gas screen and bipolar plate. The dashed curve in Figure 1 shows the increase in capacity discharged and the increase in watts and watt-hours. The greatest change is noticed of the 250 A level where the hydrogen gas concentration depletion is less than that of the 500 A rate. An increase in ratio of off to on time may have improved the pulsed performance, particularly at higher rates.

Figure 2 shows the relationship of energy delivered on discharge to battery temperature. The cooling configuration dictates that temperatures were equal over the entire cell area. A marked increase in energy delivered and cyclic efficiency was observed at the 30 °C data point compared to both higher and lower temperatures. At temperatures lower than 30°, battery voltage increases on charge and decreases on discharge causing a net decrease in efficiency. However, above 30 °C, effects of nickel electrode charging inefficiency were seen. These results indicate that a bipolar battery with inter-cell, planer cooling plates could operate at a higher thermal system temperature than conventional single cell designs that transmit heat in a radial direction via the vessel wall. Therefore, thermal system designs would need to consider the differences in battery design.

Figure 3 shows the battery voltage profile response to pulse discharges of 500 A. Only the first four pulses are shown here, although 155 pulses (21.5 A-hr) were discharged. The instantaneous battery voltage drop during the pulse increased from 1.4 to 2.2 V from beginning to end. This increase in voltage drop indicates that a 50 percent change in effective internal cell impedance occurred.

Figure 4 shows the voltage profile for a one pulse maximum power test. A 1500 A 1 sec pulse was delivered. Battery voltage, measured at the external terminals of the vessel, was 4.0 V resulting in a power level of 6 kW. The

instantaneous voltage drop was 8 V for the 1500 A pulse. Using these values, a cell resistance of about $0.5 \mu\Omega$ was calculated.

CYCLE TESTS

The battery was cycled at a low-earth-orbit (LEO) regime of 60 min charge and 30-min discharge to a depth of 40 percent. The hydrogen pressure was 200 psi and the coolant temperature was set at 20 °C. The discharge current was a constant 4 A and the charge was a constant current of 22 A (10 percent overcharge) for the first 300 cycles. The discharge current and charge current were lowered to 32 and 18 A, respectively, because these values were more representative of the actual capacity obtained at the LEO rate.

After 100 LEO cycles the amount of overcharge was increased to 15 percent in order to maintain proper end-of-discharge (EOD) voltages. The EOD voltage of Cell 6 had declined a total of 0.680 V in 100 cycles, reaching 0.5 V before the 30 min discharge was completed. Cell 6 was then individually charged for 16 hr at 5 A (cycle 206) and discharged at 12 A. This capacity check indicated a 25 to 30 percent loss in low-rate capacity to 1.0 V compared to the other nine cells (fig. 5).

The electronic voltage sensors were set to terminate discharge when any cell voltage reached 0.5 V. Therefore, Cell 6 was shunted at cycle 207 with a conductor to avoid overcharging the other cells when Cell 6 would reach 0.5 V prior to the 30-min discharge. The hydrogen electrode was considered as a possible cause of the problem. High discharge polarizations were observed with this battery as compared to previous bipolar batteries built. The total hydrogen electrode was comprised of three 8 by 8 in. sections. If one section became inactive due to improper electrolyte volume, the pattern of current density distribution through the cell would cause an even greater internal resistance and possibly inactive areas of the nickel electrode. This imbalance of electrolyte volume within the electrode could develop over a period of time. Special testing in small cells has indicated poor discharge performance, resulting in a decrease in discharge capacity in cells that were built with wholly or partially defective electrodes. Figure 6 shows a LEO cycle discharge profile for Cell 6 at cycle 205, Cell 10 at cycle 3000 and a battery averaged profile at cycle 3000. The capacity loss of Cell 10 after 3000 cycles had approached that of Cell 6 after 205 cycles. However, the slope of the voltage profile following the knee of the curve for Cell 10 was not as steep as that of Cell 6 and the voltage had not reached 0.800 V by EOD. The capacity of Cell 10 had declined 30 percent in 3000 LEO cycles, but did not affect battery charge or discharge operation. A problem with a section of hydrogen electrode was also suspected in Cell 10.

The battery continues to life cycle at 40 percent DOD and has accrued 3200 cycles as of 5/86. The discharge voltage profiles of the other eight cells have remained unchanged during these cycles and the averaged voltage is shown in figure 6. The average EOD voltage was 1.18 V. This value was lower than expected for a 40 percent DOD and would be typical for 80 percent DOD. The hydrogen electrode vendor was approached on this matter of possible electrode problems. A specification change in the supplier's materials used for the electrodes could be the source of these difficulties experienced with the hydrogen electrodes.

Figure 7 shows the voltage and temperature profiles for Cell 1 during cycle 3000. The temperature shown is the center of the nickel electrode in Cell 1. The temperature plot shows a uniform average cycle temperature with a 2-°C rise during the end of charge. This also demonstrates the effectiveness of the cooling design to maintain uniform temperatures throughout the battery.

CONCLUSIONS

The parametric tests conducted on the first actively cooled bipolar nickel-hydrogen battery demonstrates its feasibility. The results are comparable to previous Lewis designs except for high rate performance. The pulse tests conducted suggest an insufficient gas access to the hydrogen electrode which has resulted in increased polarization. This area has been addressed in other designs for high discharge rates.

The thermal aspects of this battery allow cooling system temperatures of about 30 °C for maximum power efficiency. Battery operation in this temperature range of 30 °C could have an impact on solar array and radiator sizing.

The battery has achieved 3200 LEO cycles at 40 percent DOD. The discharge voltage has shown no degradation, with the exception of Cells 6 and 10 that may contain defective hydrogen electrodes. The voltage performance of this battery was less than predicted and hydrogen electrodes with high polarization have been identified as a possible cause. However, a valid data base is being generated on the overall concept of an actively cooled bipolar battery.

Lewis is working toward establishing a baseline design that would require only simple low cost modifications to the baseline design for integration into various applications. The successful application of active cooling is a major step in developing this baseline design.

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TABLE I. - TABULATED TEST MATRIX DATA AT 200 PSI

Charge rate	Discharge rate	Temperature, °C	Ampere-hours, out	Watt-hours, in	Watt-hours, out	Energy efficiency, %	End-of-discharge battery voltage
C	2C	0	42.4	879	468	53	9.3
C	C	↓	44.4	882	533	60	10.4
C	C/4	↓	49.3	883	629	71	10.8
C/2	2C	↓	43.8	845	469	55	8.8
C/2	C	↓	46	845	545	64	10.2
C/2	C/4	↓	51.5	851	655	77	10.4
C	2C	10	43.6	856	497	58	9.5
C	C	↓	46	860	557	65	9.8
C	C/4	↓	51	856	648	75	10.1
C/2	2C	↓	43.5	831	489	59	9.3
C/2	C	↓	45	834	539	65	9.9
C/2	C/4	↓	52	840	656	78	9.9
C	2C	20	45.5	843	529	63	9.5
C	C	↓	47.5	842	582	69	10.1
C	C/4	↓	51.5	818	652	80	8.4
C/2	2C	↓	45	822	524	64	9.5
C/2	C	↓	48	820	587	72	9.7
C/2	C/4	↓	51.5	820	655	80	9.6
C	2C	30	43	834	505	60	10.1
C	C	↓	46	834	560	67	10.5
C	C/4	↓	50	832	639	77	9.5
C/2	2C	↓	40	818	470	57	10.5
C/2	C	↓	44	813	536	66	9.4
C/2	C/4	↓	49	818	629	77	9.7
C	C	40	41.8	824	520	63	10.6
C/2	C	40	41.5	809	516	64	10.5

TABLE II. - TABULATED TEST MATRIX DATA AT 400 PSI

Charge rate	Discharge rate	Temperature, °C	Ampere-hours, out	Watt-hours, in	Watt-hours, out	Energy efficiency, %	End-of-discharge battery voltage
C	C	0	37	890	452	51	10.9
C/2	C	0	39	857	470	55	10.7
C	C	10	37.8	870	466	53.5	11.0
C/2	C	10	38.5	841	474	56	10.8
C	C	20	39.4	851	490	57	11.0
C/2	C	20	39.6	829	495	60	10.8
C	C	30	42.2	836	523	62.5	9.3
C/2	C	30	42.2	824	523	63.5	9.1
C	C	40	45.5	827	569	69	8.7
C/2	C	40	41.8	816	521	64	8.9

TABLE III. - CHARACTERIZATION TEST MATRIX

[2 hr, 32.5 A charge; C rate (50 A) discharge.]

Temperature, °C	Pressure base, psi	Ampere-hours, out	Watt-hours, in	Watt-hours, out	Watt-hours, eff., %	End-of-discharge battery voltage
0	400	44	1015	514	51	9.7
10	400	44	1000	524	52	9.9
20	400	46	978	554	56.5	9.0
30	400	48	967	575	60	8.9
40	400	45	980	553	56.5	8.9
0	200	43	1018	502	49	9.7
10	200	42	1007	502	50	10
20	200	42	975	506	52	10.3
30	200	44	970	532	55	9.8
40	200	42	957	510	53	8.6

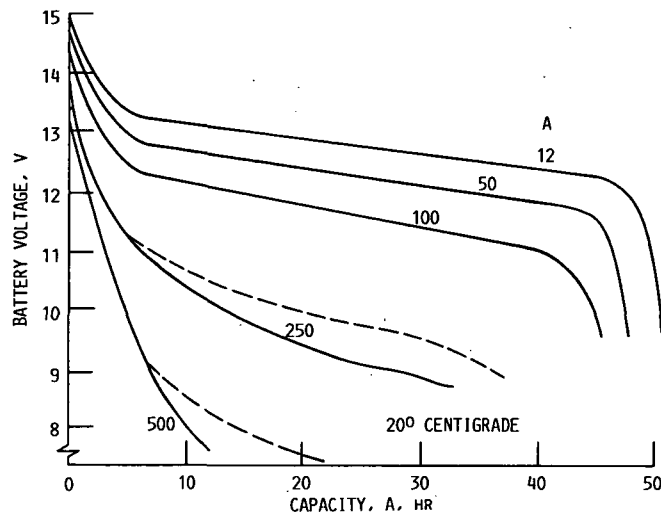


FIGURE 1. - CAPACITY VERSUS DISCHARGE RATE.

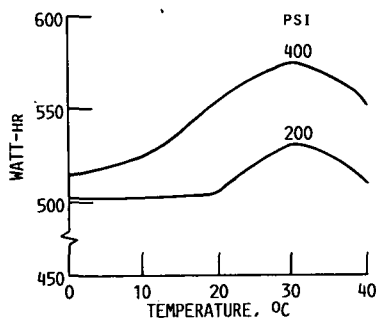


FIGURE 2. - WATT-HOURS VERSUS TEMPERATURE.

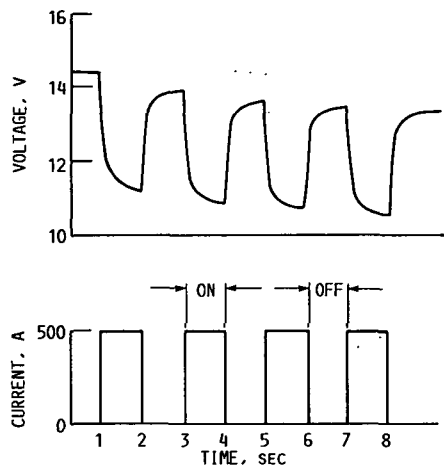


FIGURE 3. - 500 AMPERE PULSE TEST.

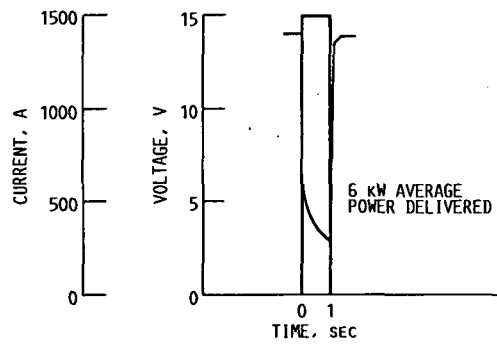


FIGURE 4. - PEAK POWER TEST.

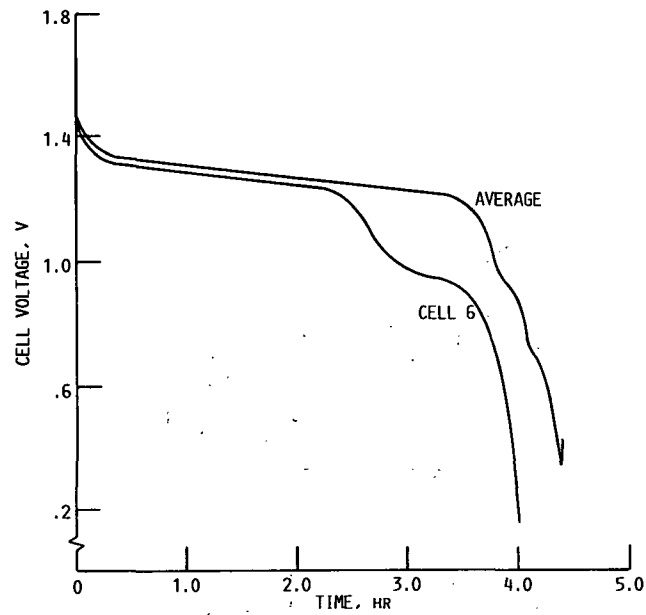


FIGURE 5. - CAPACITY MEASUREMENT, C/4 RATE.

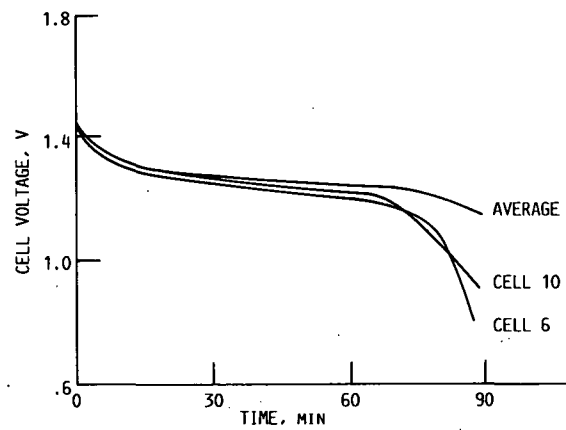


FIGURE 6. - DISCHARGE CELL VOLTAGE PROFILE.

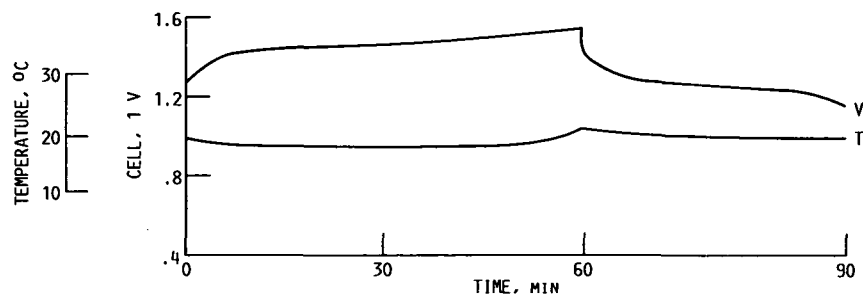


FIGURE 7. - VOLTAGE AND TEMPERATURE PROFILES FOR CYCLE 3000.

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